Interpreting the subsurface architecture of maar volcanoes using geologically constrained 3D gravity inversions

Examples from the Newer Volcanics Province, Western Victoria

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The research shown in this presentation is published in the following journal articles:

- Blaikie, T. N., J. van Otterloo, L. Ailleres, P. G. Betts, and R. A. F. Cas (2015), The erupted volumes of tephra from maar volcanoes and estimates of their VEI magnitude: Examples from the late Cenozoic Newer Volcanics Province, south-eastern Australia, Journal of Volcanology and Geothermal Research, 301(0), 81-89.

- Blaikie T. N., Ailleres L., Betts P. G. & Cas R. A. F. 2014. Interpreting subsurface volcanic structures using geologically constrained 3-D gravity inversions: Examples of maar-diatremes, Newer Volcanics Province, southeastern Australia. Journal of Geophysical Research-Solid Earth 119, 3857-3878.

- Blaikie, T.N., Ailleres, L., Betts, P.G. and Cas, R.A.F., 2014. A geophysical comparison of the diatremes of simple and complex maar volcanoes, Newer Volcanics Province, south-eastern Australia. Journal of Volcanology and Geothermal Research, 276: 64-81.

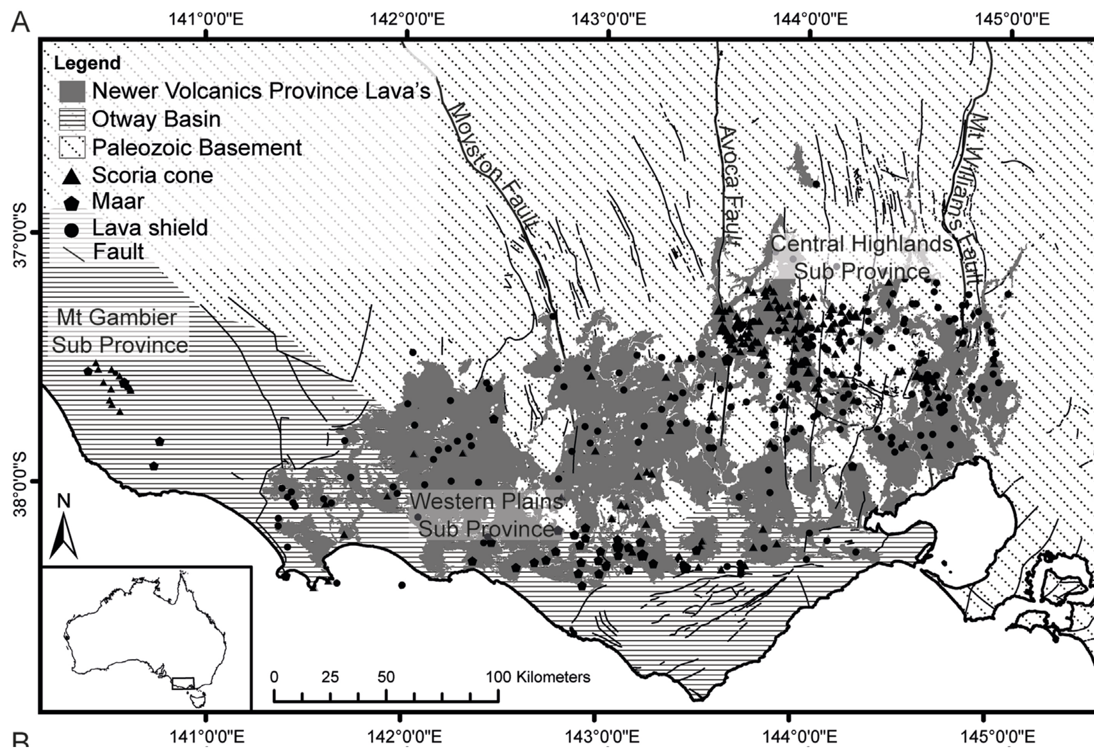
- Blaikie, T.N., Ailleres, L., Cas, R.A.F. and Betts, P.G., 2012. Three-dimensional potential field modelling of a multi-vent maar-diatreme - the Lake Coragulac maar, Newer Volcanics Province, south-eastern Australia. Journal of Volcanology and Geothermal Research, 235-236: 70-83.

Introduction

- Subsurface maar structures are not exposed within Victoria – hidden by post-eruptive sediments and lakes
- Most studies will tend to focus on the surface characteristics of edifice
  - Eg. Crater morphology, pyroclastic deposits, geochemistry
- Tells us little about the 3D subsurface morphology of the volcano
- There is a need to take a multi-disciplinary approach to research and combine physical volcanology with potential field geophysical modelling
- High geophysical contrast between the host rocks, diatreme (subsurface collapse structure) and basaltic feeder dykes
- An improved knowledge of these volcanic systems, and their hazards can be gained by **integrating geophysical and geologic data**

Geologic Background: Newer Volcanics Province

- Active intraplate basaltic volcanic province
- Volcanism spans from 4.5 Ma to 4.5 ka
- 3 sub-provinces – divided on the basis of morphology and geochemistry
- Host to over 400 eruptive centres
  - Lava flows
  - Maar volcanoes
  - Scoria cones
  - Lava shields
  - Volcanic complexes



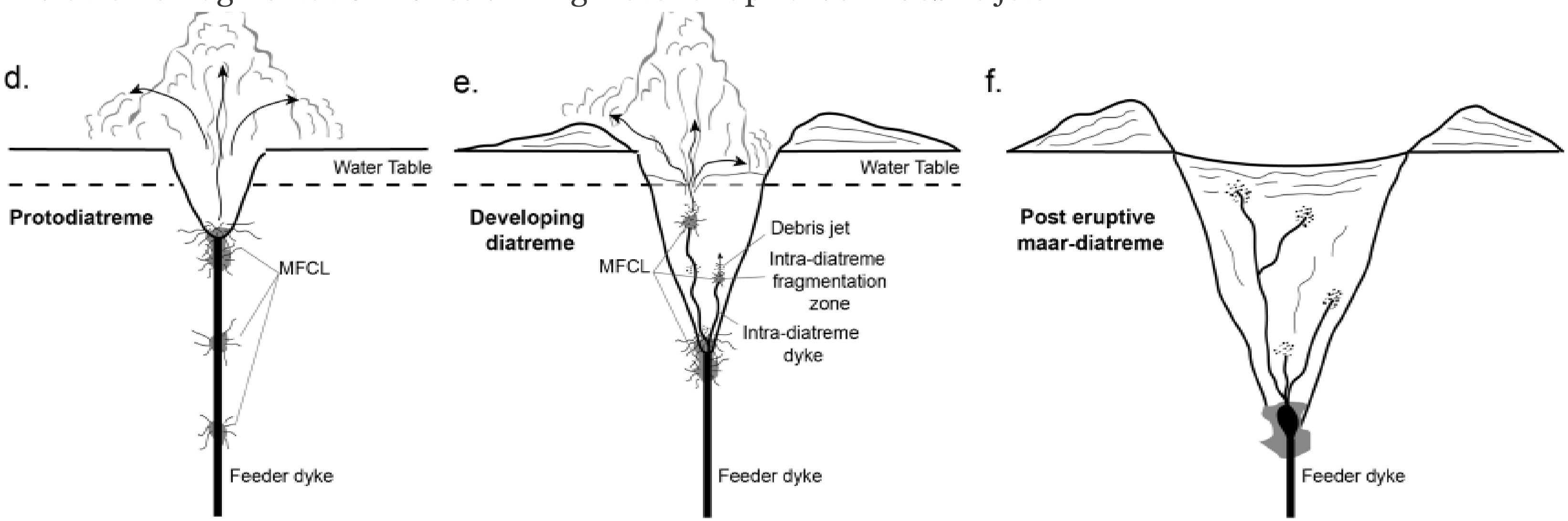
Blaikie *et al.* (2014a)

Maar volcanoes within the NVP

- 40 maars identified in the NVP
    - Simple – small, circular craters
    - Complex – large complex craters, nested scoria cones, multiple vents
- Most are hosted in weakly lithified sediments of the Otway Basin
- Original crater rims are preserved, diatremes are not exposed
    - **Apply geophysical methods to image the subsurface morphology**

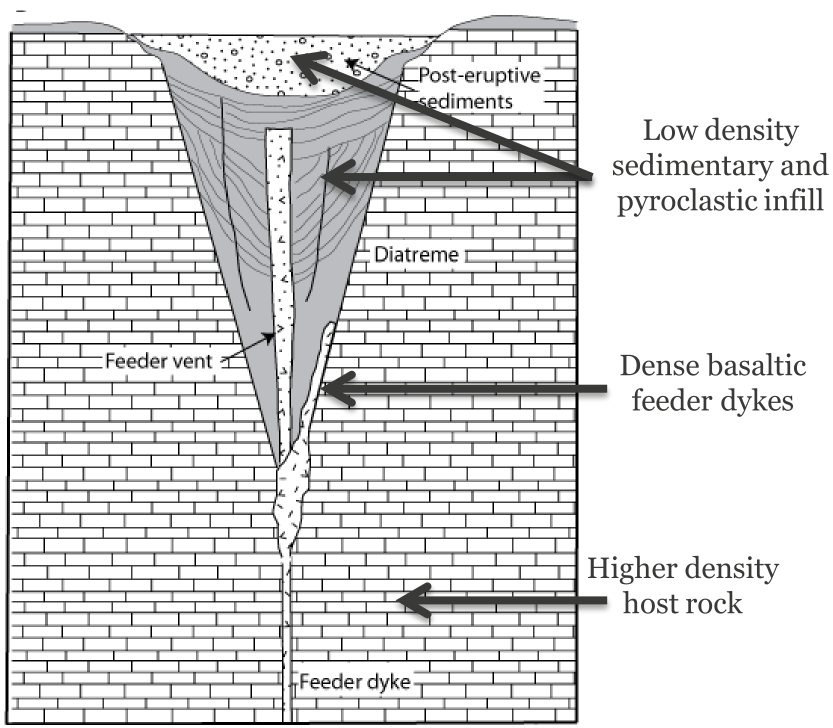
Maar volcanoes - formation

- Magma rises in a dyke and interacts with groundwater, forming phreatomagmatic explosions.
- Explosions can occur at any depth, but will typically only erupt when explosions are shallow (<200 m). These explosions excavate a small crater and form a diatreme which is infilled with pyroclastic and host rock debris.
- During the eruption, dykes can extend into the fill of the diatreme, forming irregular intrusions due to its heterogeneous and unconsolidated nature. The dykes form new sites for phreatomagmatic explosions in what is termed an ‘intra-diatreme fragmentation zone’.
- The diatreme fill, is mixed through the diatreme by explosions occurring within the root zone or at intra-diatreme fragmentation zones driving material upwards in debris jets.

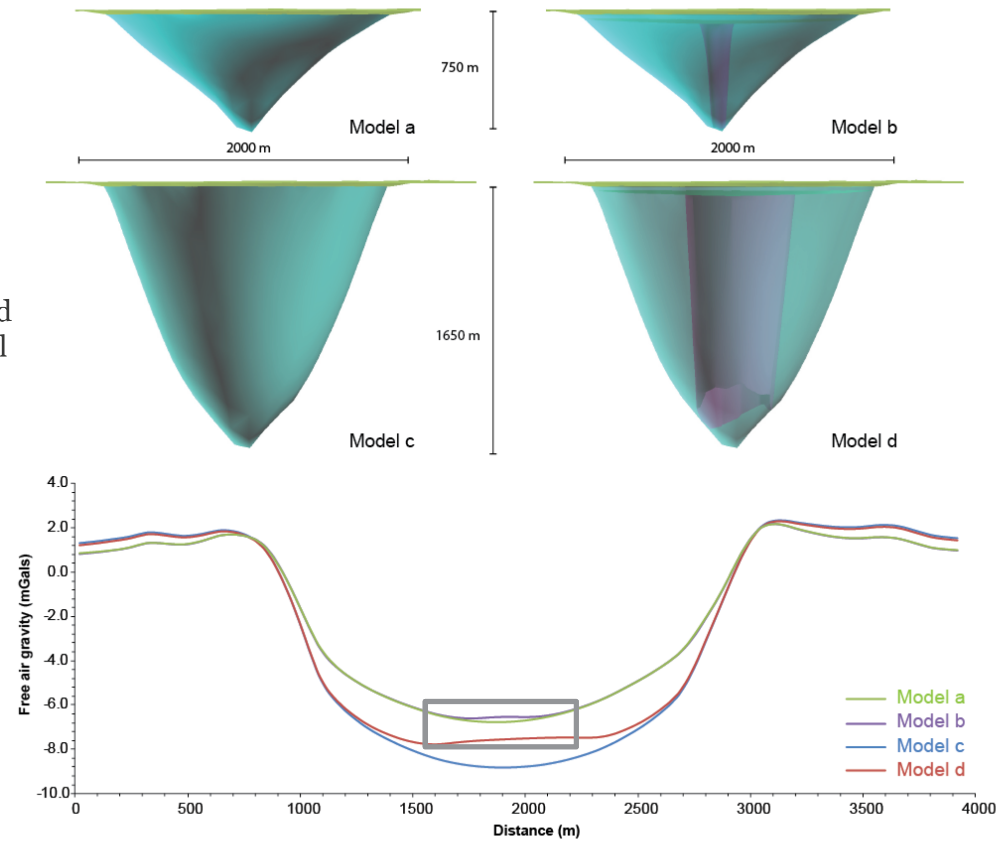


Synthetic models

- Prior to acquiring gravity and magnetic data, we need an idea of anomaly wavelengths, so a survey can be designed to detect those anomalies
- Expect gravity and magnetic low with local highs within the centre of the crater



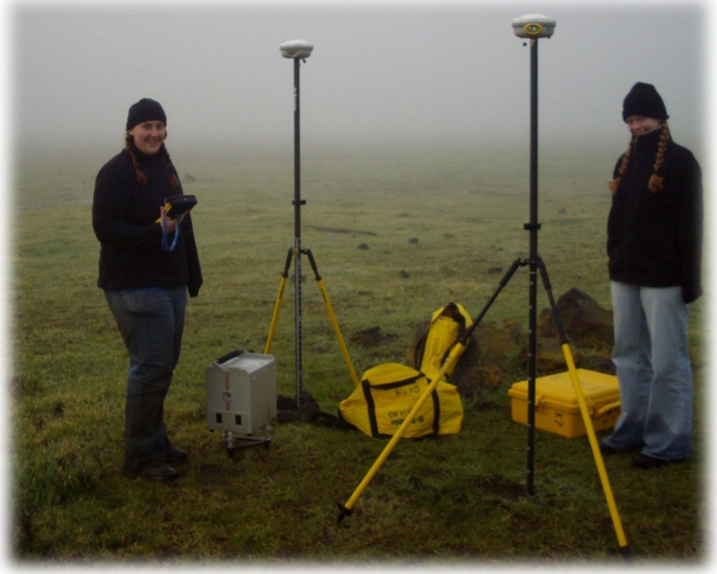
Modified from (Lorenz 1986)



Blaikie *et al.* (2014b)

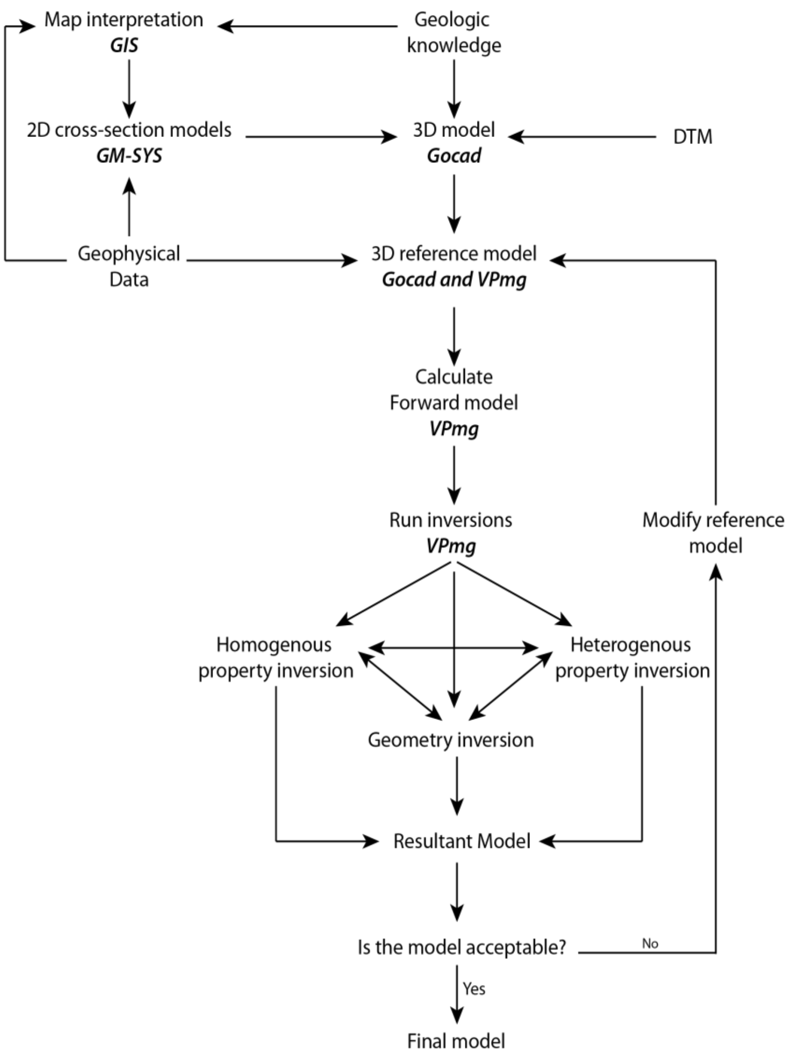
Geophysical surveys

- High-resolution gravity (15-20 m spacing) and magnetic data is acquired along several traverses



Interpretation strategy

- There are many strategies for modelling of potential field data. The workflow presented here focusses on integrating geologic data and interpretations of gridded aeromagnetic and gravity data into forward and inverse models.
  - This process can produce more robust and realistic results because models are constrained at every stage of the modelling process.



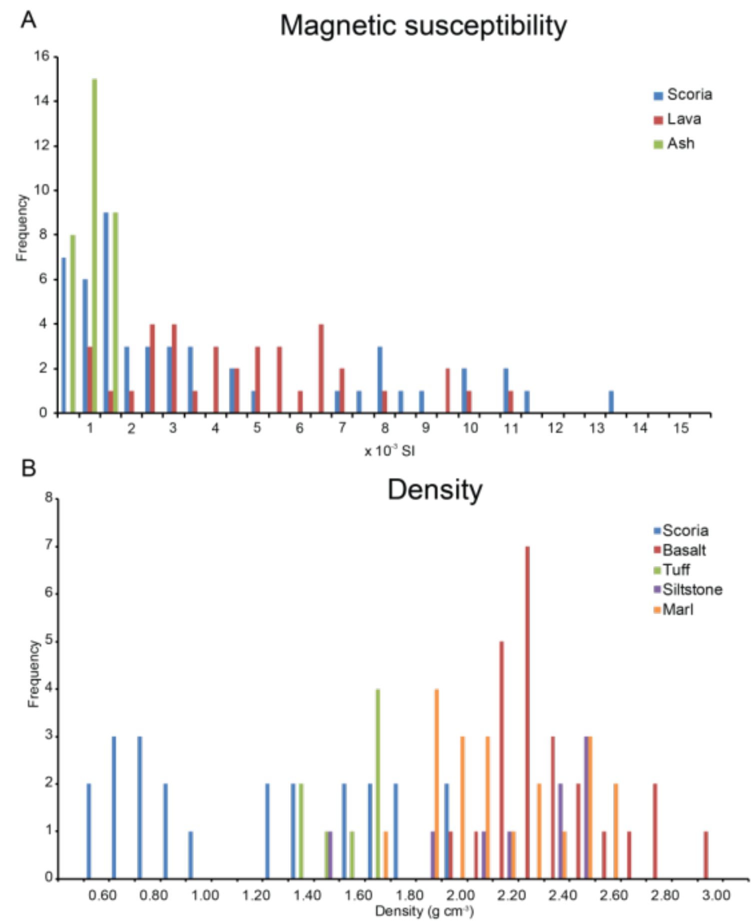
Blaikie et al. (2014b)

Model Constraints

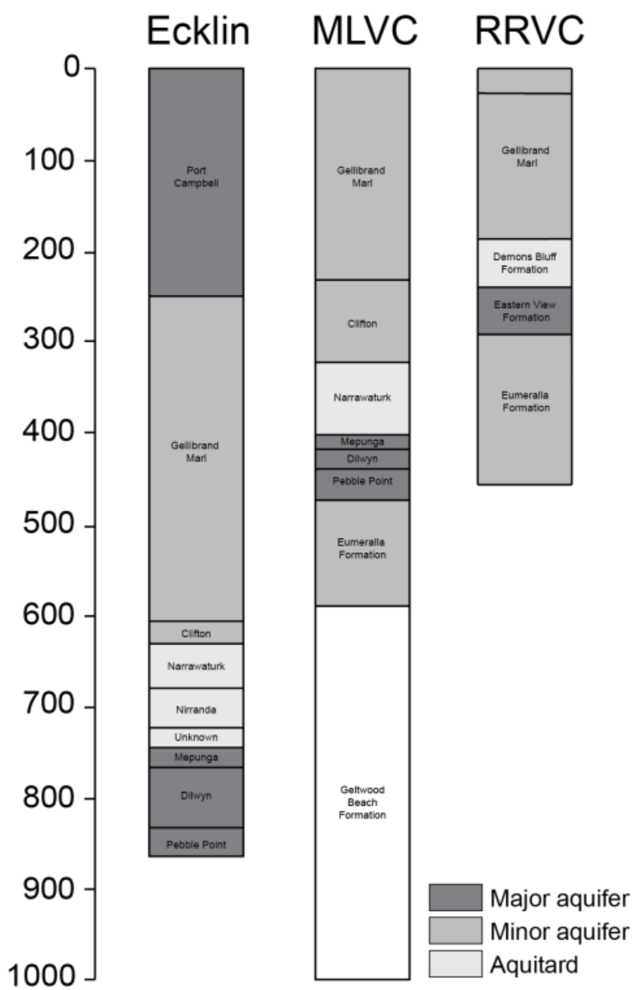
- Potential field models are non-unique, and many models can be constructed that may reproduce the observed anomalies. It is therefore important to constrain the interpretation with geologic data (eg. rock properties, field observations) if you want to obtain meaningful results.

- Incorporate geologic information into the forward model:
  - Regional geology
  - Surface observations (deposits – accidental lithics)
  - Petrophysics (eg. Density & magnetic susceptibility)

- Restrict changes to the model during inversion
  - Fix geometries
  - Restrict changes to a property
  - Restrict the amount of change in the model per iteration



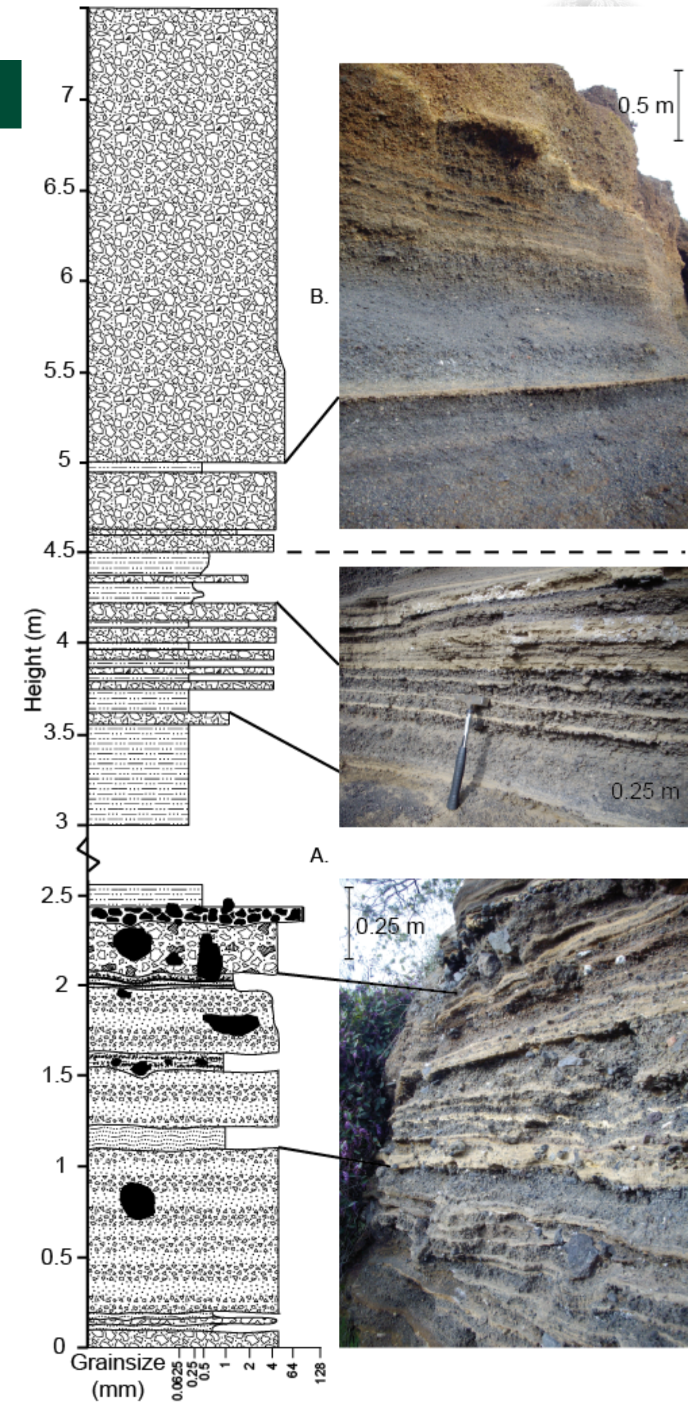
Model Constraints



- Maar volcanoes formed by interaction of magma with groundwater
  - An understanding of the stratigraphy and key aquifers within the region is required

Model Constraints

- Some knowledge of the eruption history can help constrain the interpretation
  - Bomb impact structures
  - Base surges
    - Identify number and location of vents
- Eruption styles
  - Shallow vs. deep levels of fragmentation

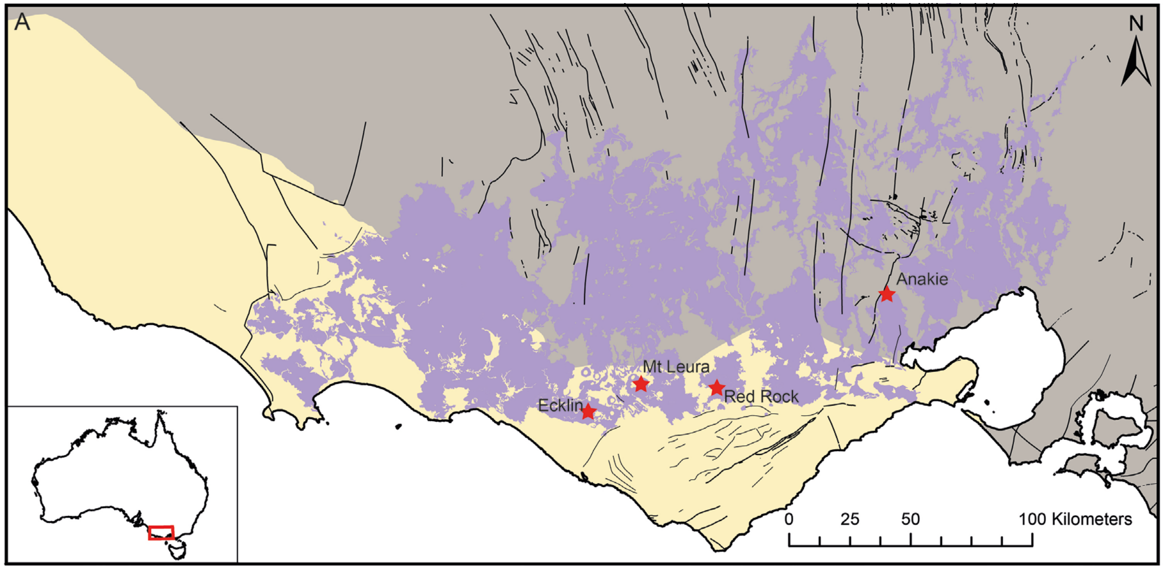


Case Studies of maars within the NVP

- Ecklin maar
- Red Rock Volcanic Complex
- Mt Leura

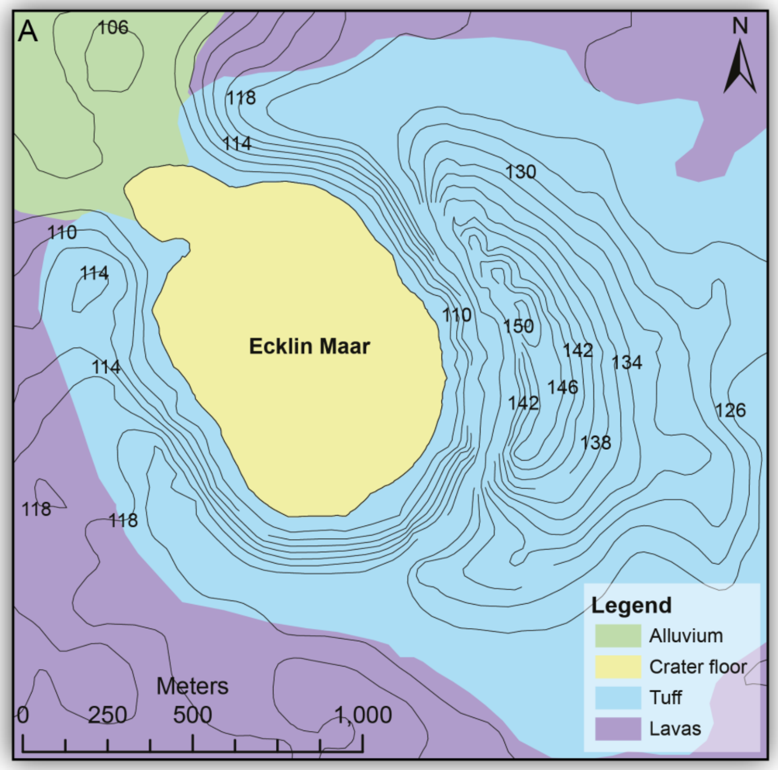
Hosted in sediments of the Otway Basin

Porosity controlled aquifer



Ecklin Maar

- Simple maar volcano approximately 800 x 1000 m in size
- Hosted in weakly lithified sediments
- Phreatomagmatic eruptive style



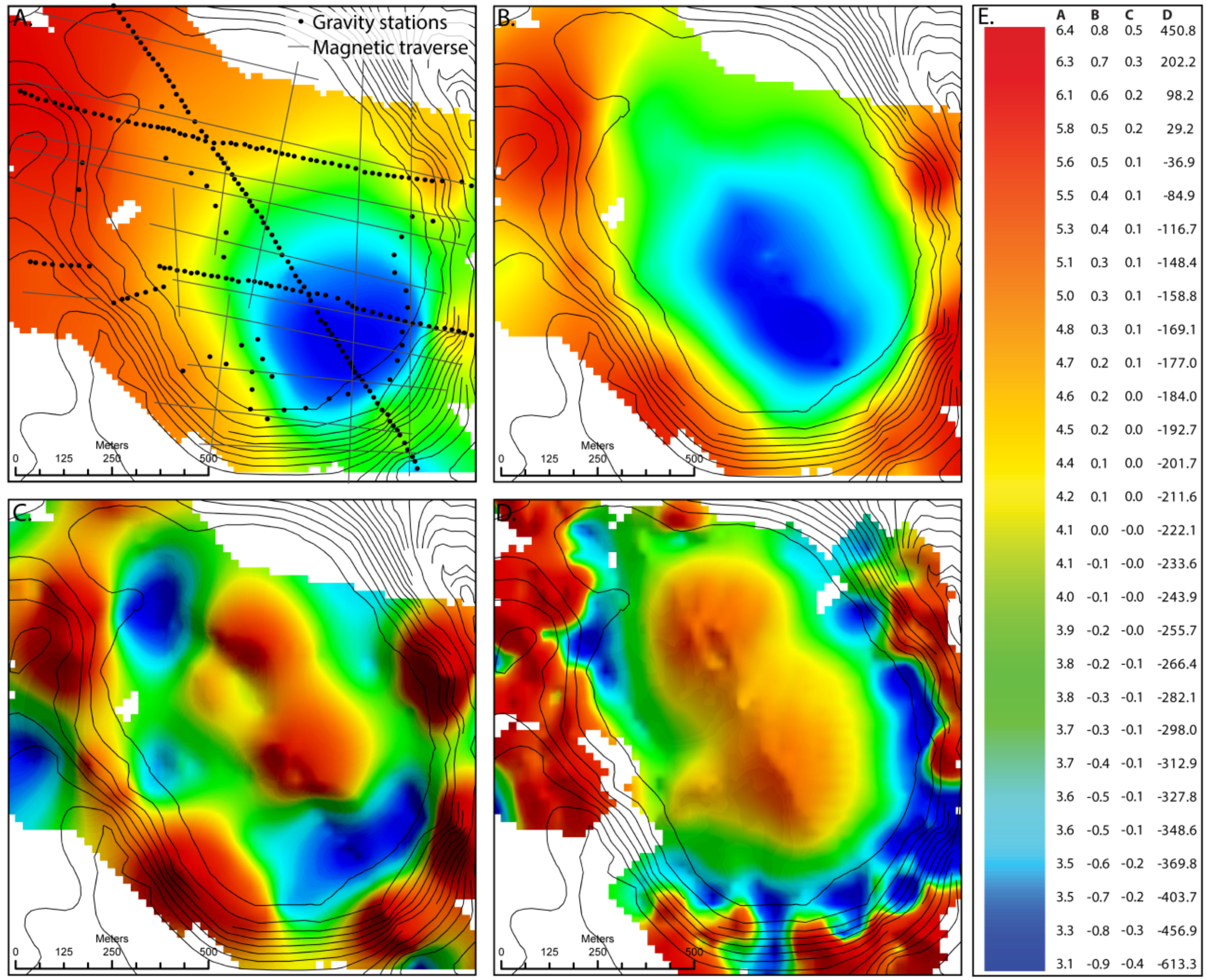
Ecklin Maar

Data:

A. **Bouguer anomaly,**
B. **Bouguer anomaly with regional trend removed.**
C. **800 m high pass filter of Bouguer anomaly.**
D. **RTP magnetic data**

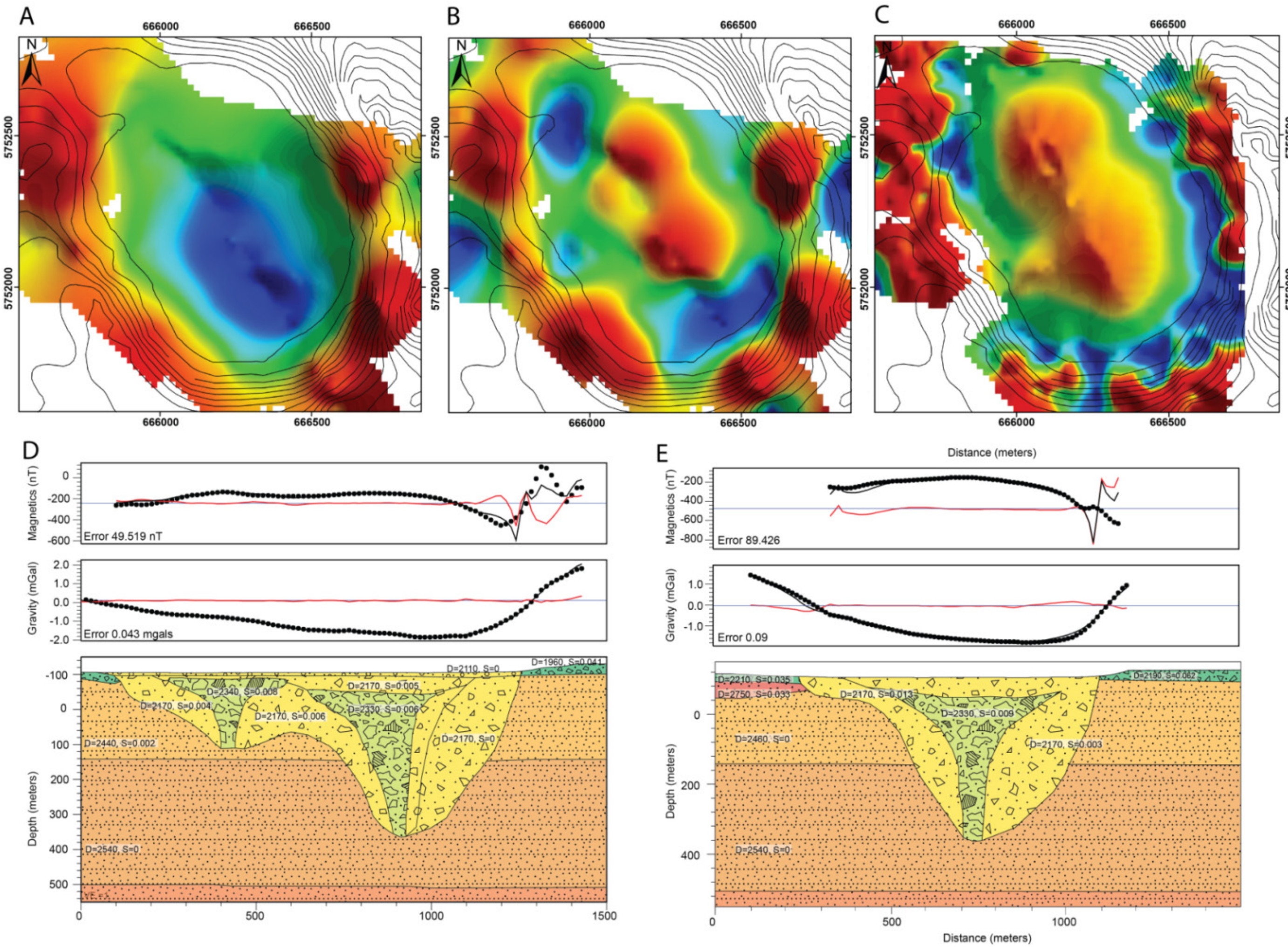
Interpretation:

A gravity low is observed over the maar crater, with a greater negative amplitude in the south of the maar. A high-pass filter of the data enhances two low amplitude positive gravity anomalies which correspond to the magnetic anomalies identified within the crater.



Blaikie et. al., 2014

Ecklin Maar



Gravity low observed across the maar, with a greater negative amplitude observed in the southern end – suggests deeper diatreme

- Maximum depth of diatreme constrained to 500 m bsl by accidental lithic fragments in maar-rim deposits

Positive gravity and magnetic anomalies suggest 2 vents

- Confirmed by ballistic impact sag structures and base surge deposits

Ecklin Maar

- Several cross-cutting 2D forward models are used to define the 3D geometry of the maar diatreme.
- The 3D model is used as a starting reference model for 3D geometry and property inversions.

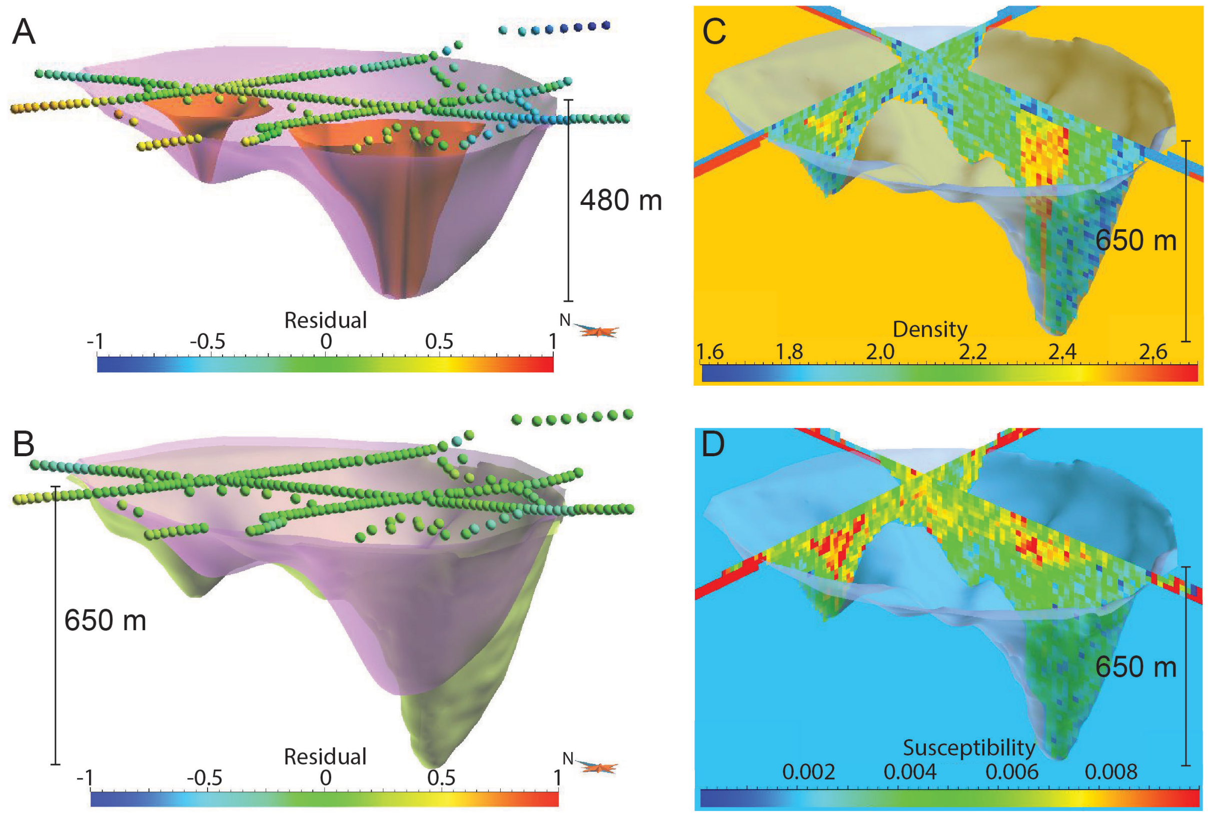
Data and interpretation:

A) 3D reference model showing the misfit calculated at each observation point (blues/reds = high levels of misfit, green = low levels of misfit)

B) Original (purple) and optimised (green) diatreme geometry showing reduced misfit

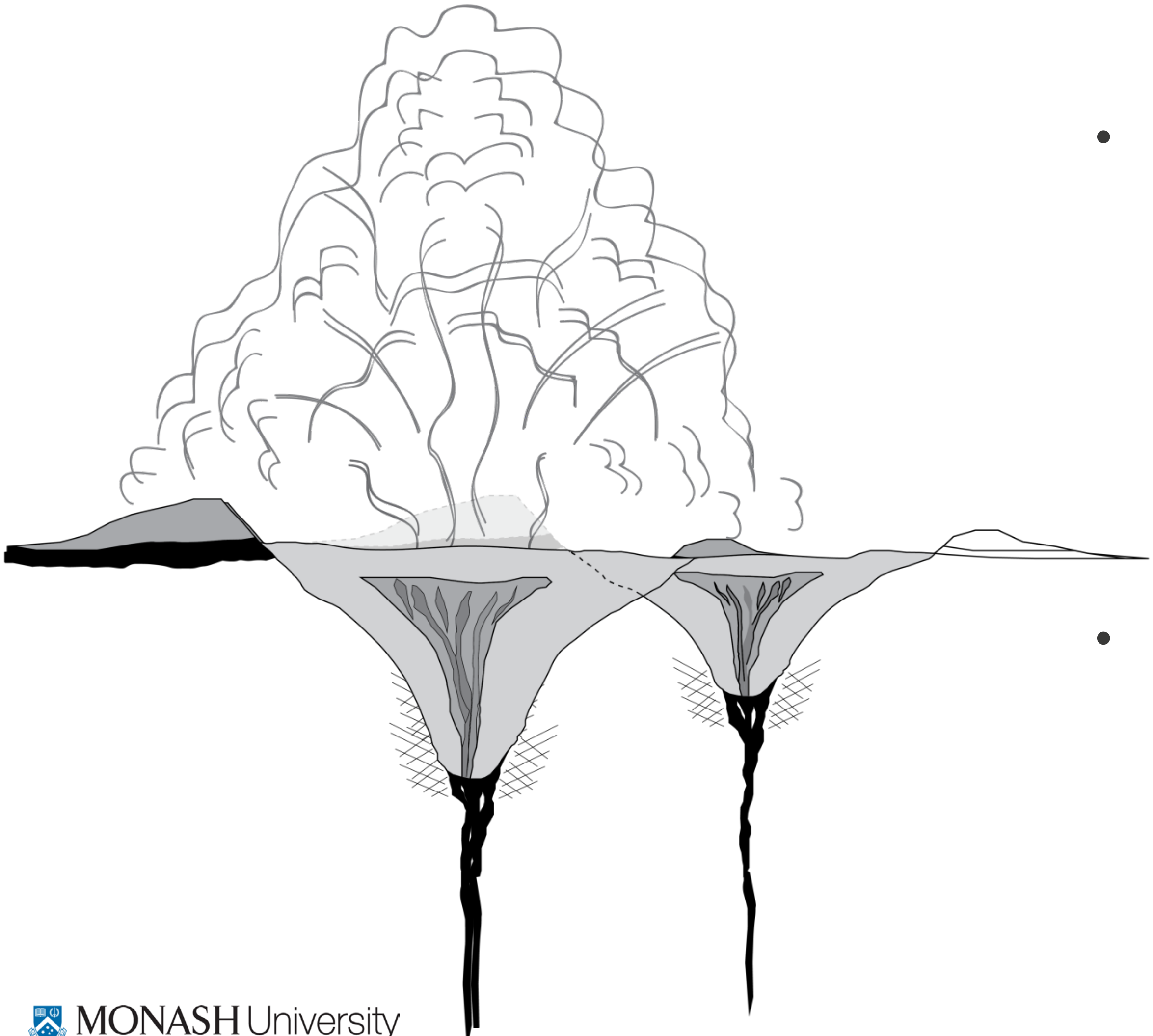
C) Vertical slices showing optimised density distribution through stochastic heterogeneous inversion (colours represent density of vertical slices).

D) Vertical slices showing optimised magnetic susceptibility distribution through stochastic heterogeneous inversion (colours represent magnetic susceptibility of vertical slices).



Blaikie et. al., 2014

Volcanic Evolution

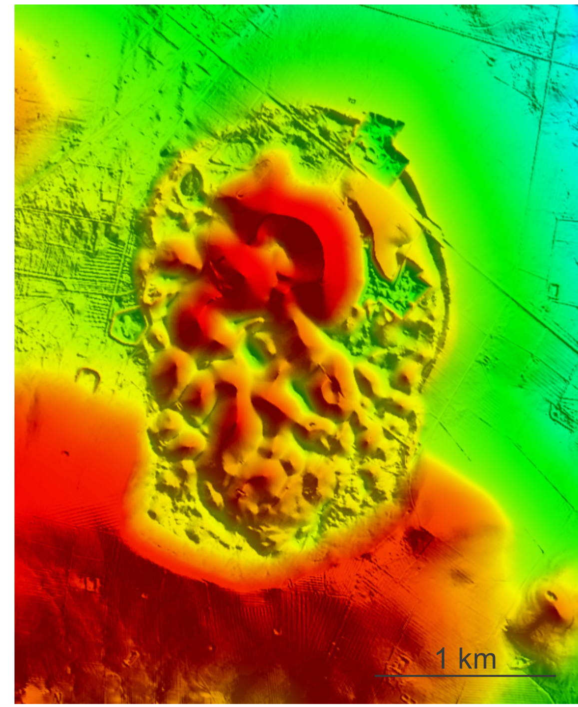


- Initial eruption occurs in the north vent
  - Depth of magma-water interaction remains at shallow levels

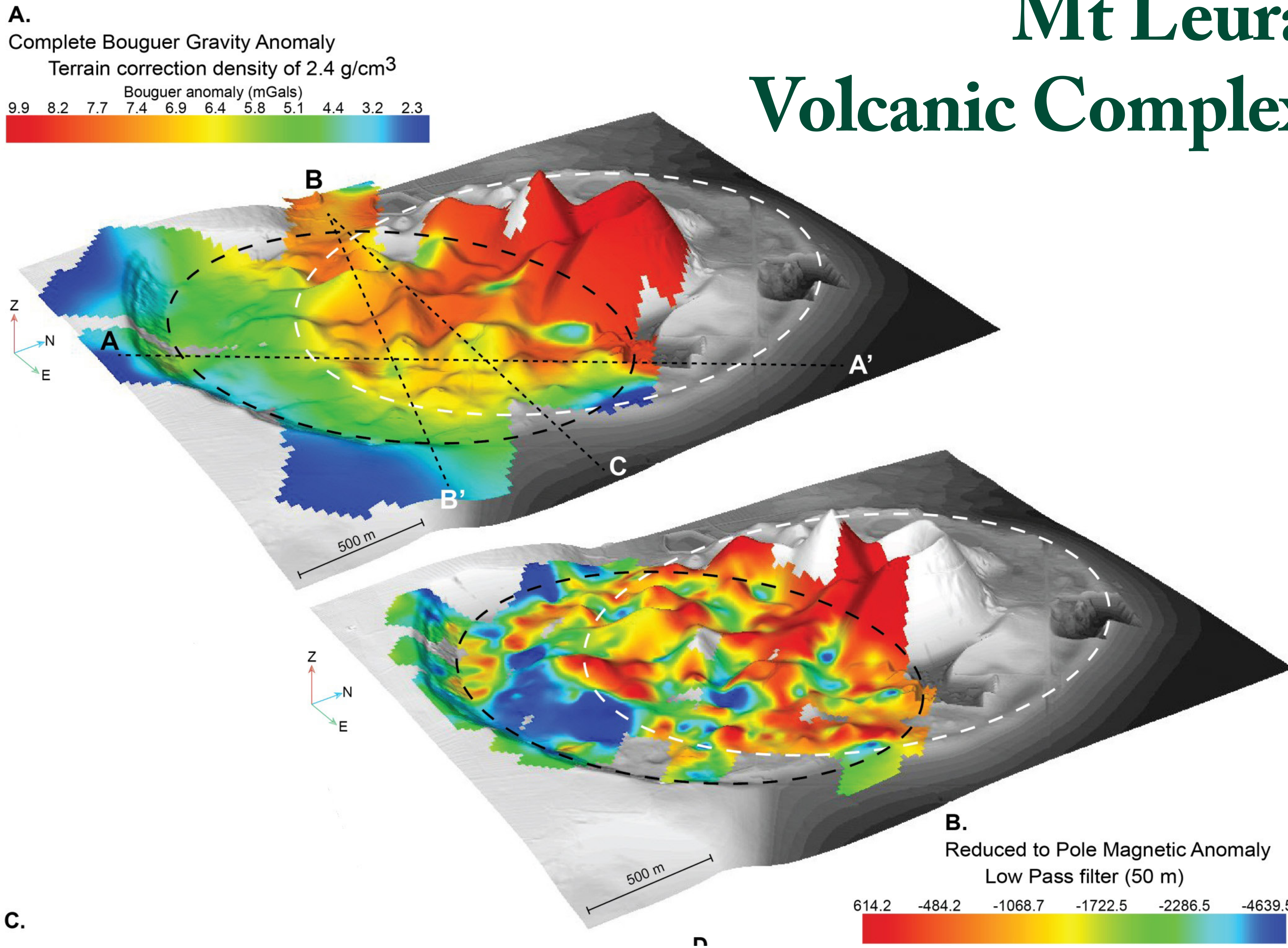
- Vent migrates to the south
  - Depth of magma-water interaction propagates downwards

Mt Leura Volcanic Complex

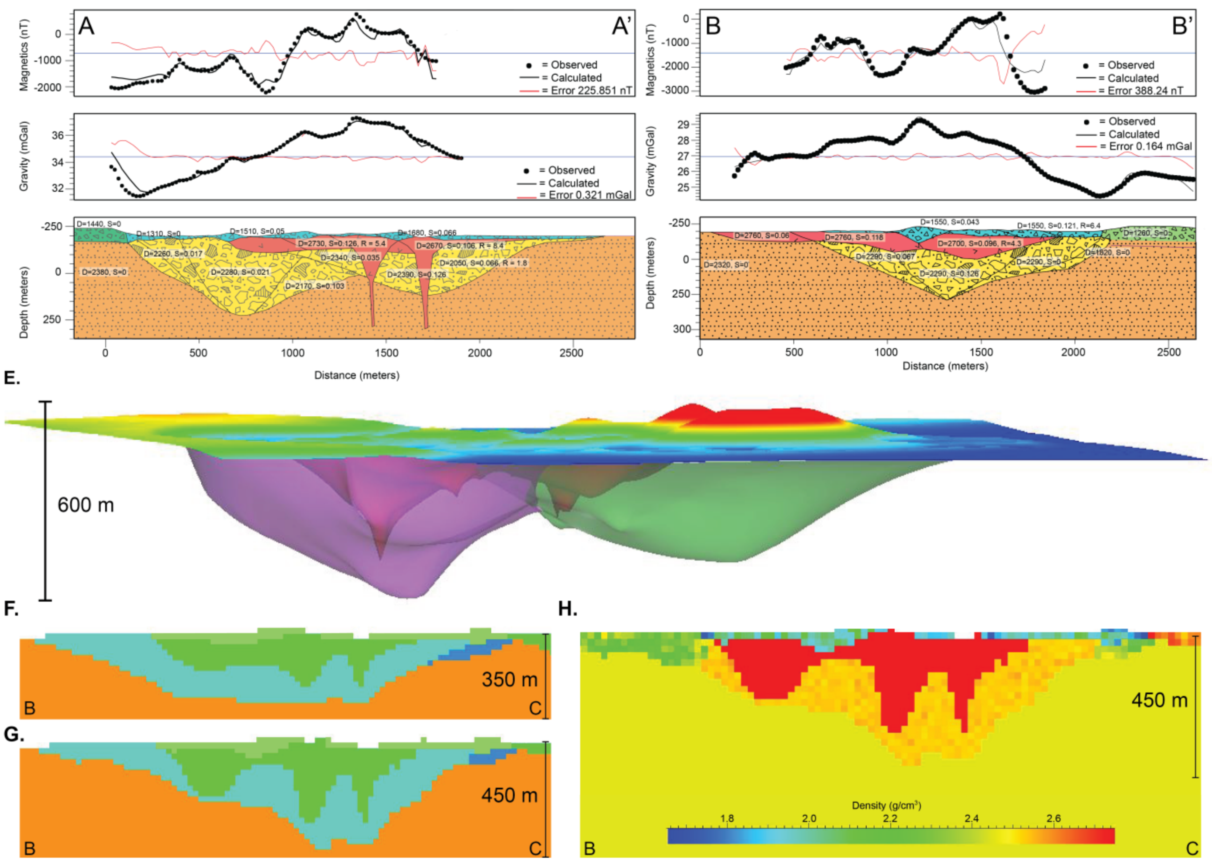
- Nested maar and scoria cone complex
- 1.5 x 2.5 km in size
- Early phreatomagmatic phase formed maar and tuff ring
- Later magmatic phase filled craters with lava and formed nested cones

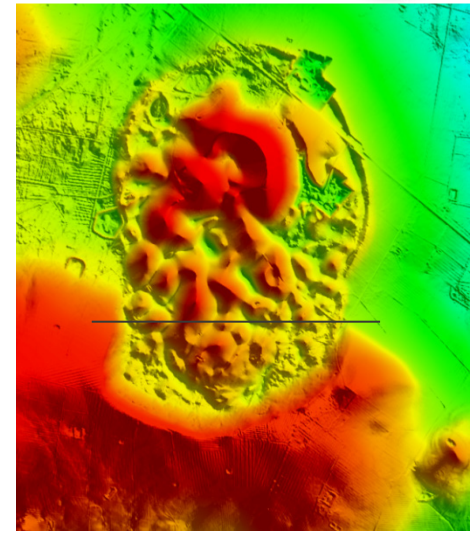


Mt Leura Volcanic Complex



Mt Leura Volcanic Complex

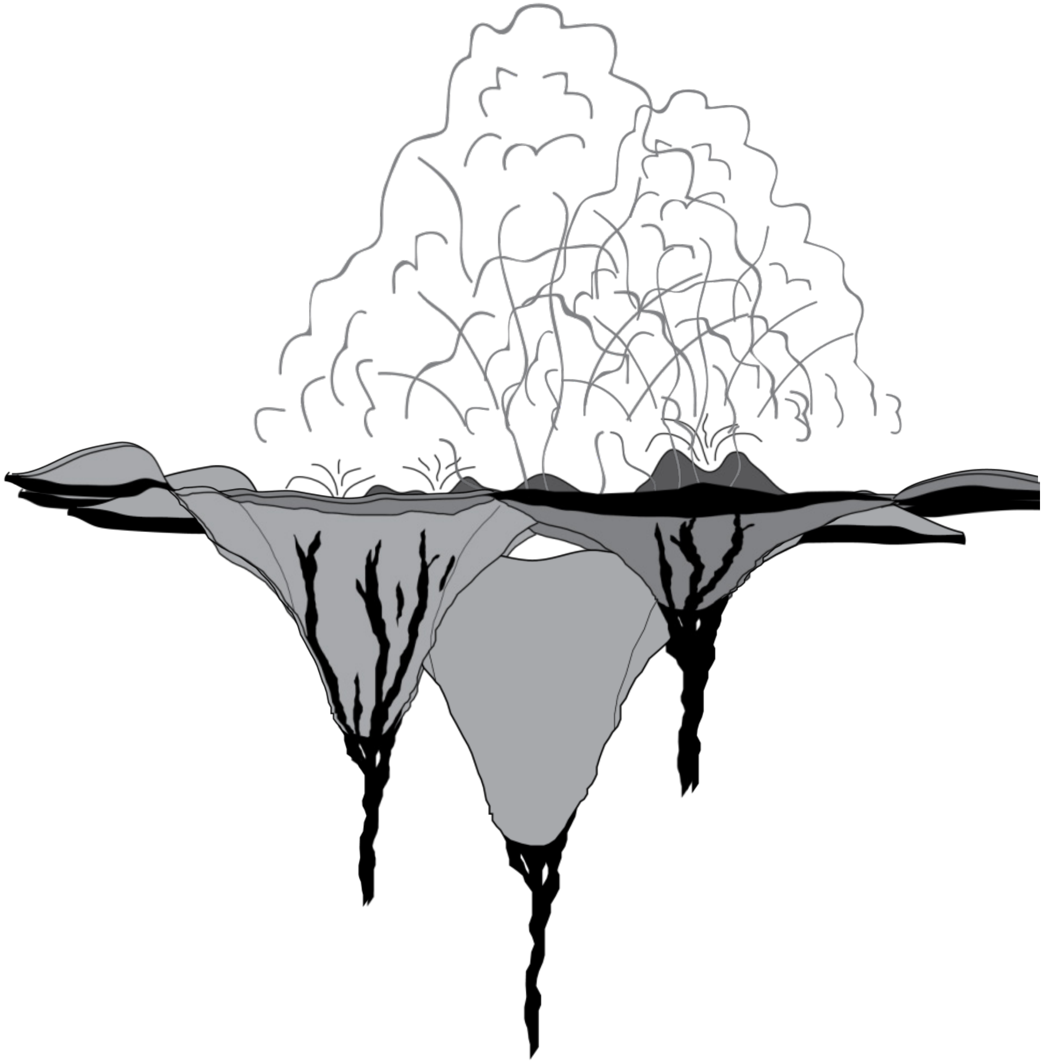




Broad shallow maar-diatreme

- Craters filled with lava
  - Observed in deeper quarry exposures
- Complex overlain with thick scoria deposits from the eruption of 18 scoria/spatter cones

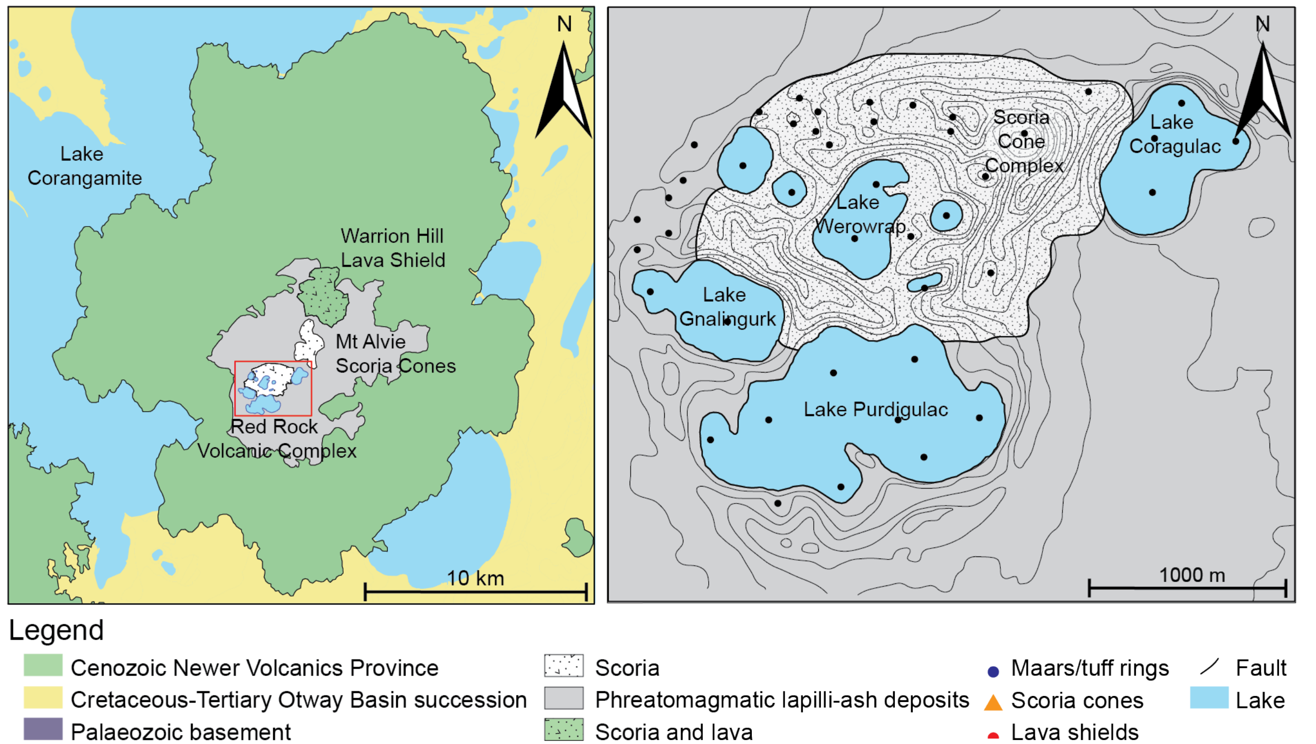
Mt Leura - Evolution



- Initial eruption forming maar in south of complex
- Vent migrates to form tuff ring in north of complex
- Eruption style switches to effusive, in-fills tuff crater with lava
- Explosive magmatic eruptive phase forming scoria cone complex

Red Rock Volcanic Complex

- One of the most complex volcanic centres in the NVP
- Multiple maars and nested scoria cones
    - ➢ Single vent maar craters 20 – 30 m in diameter
    - ➢ Multiple vent maar craters up to 1.4 km wide
- Gravity and magnetic data has been acquired across each of the maars
- Complex geophysical response

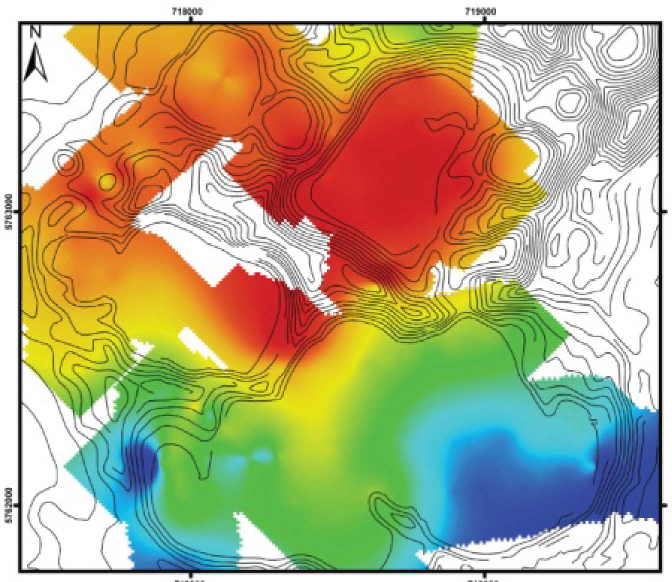


Modified after Blaikie *et al.* 2012

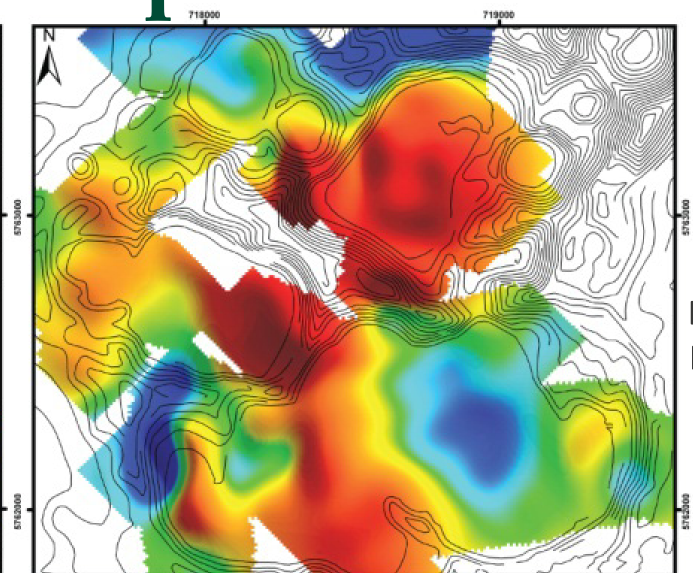
Monash Structural Geophysics Group

Red Rock Volcanic Complex

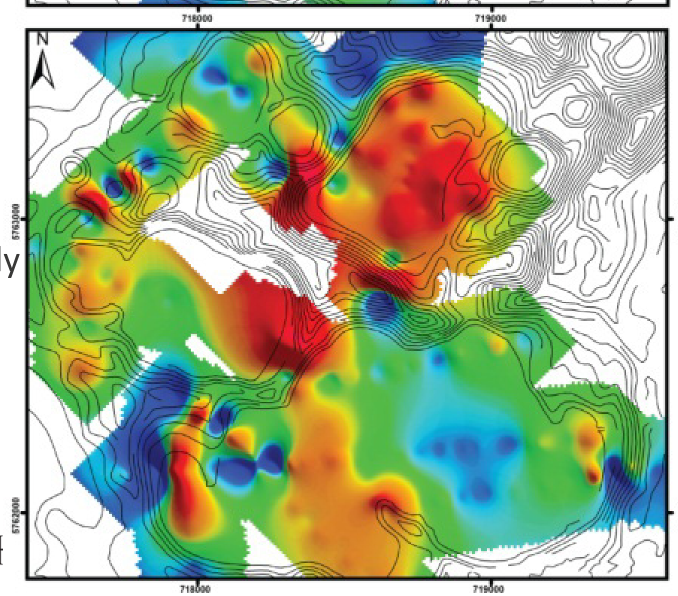
Bouguer anomaly



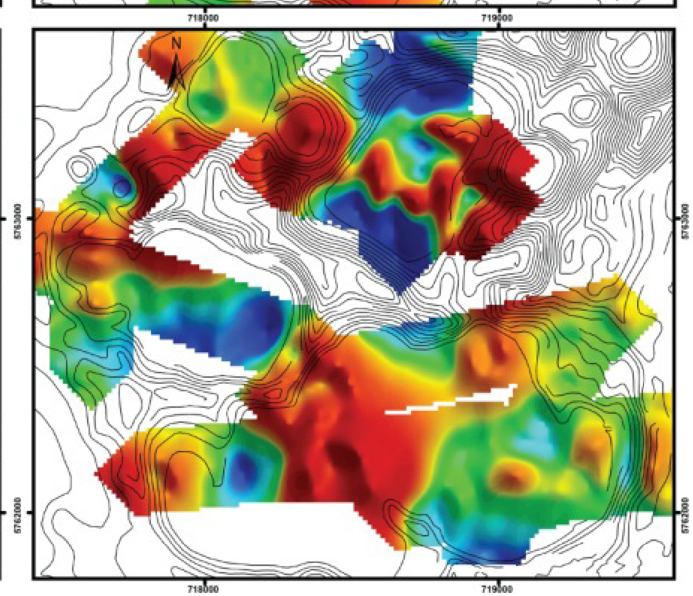
Bouguer anomaly Regional gradient removed



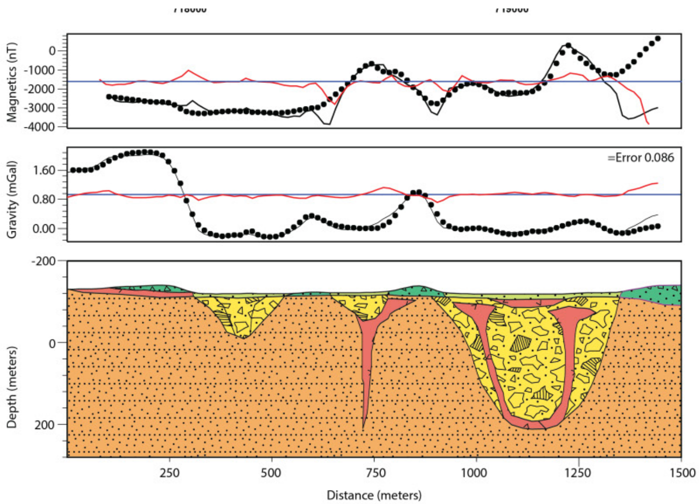
Bouguer anomaly 1st Vertical derivative

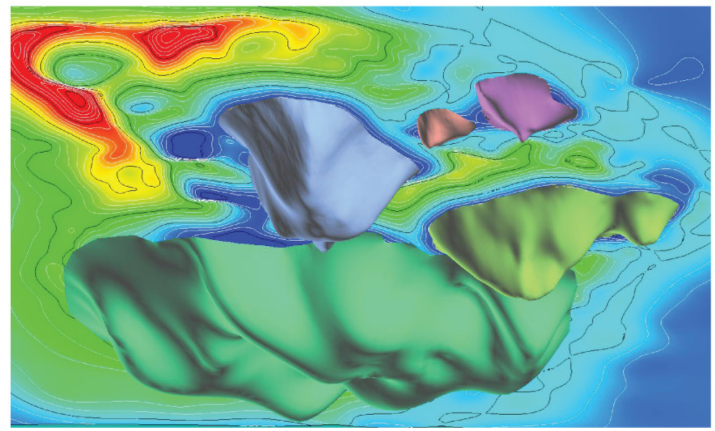


Reduced to Pole Magnetics



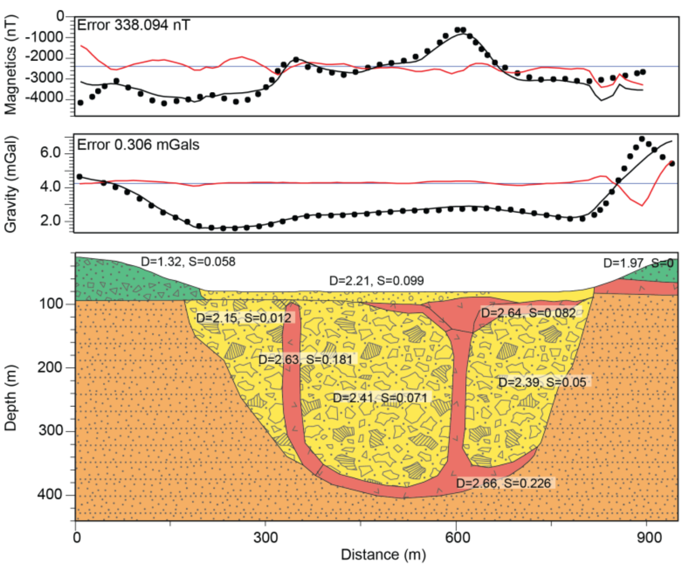
Red Rock Volcanic Complex

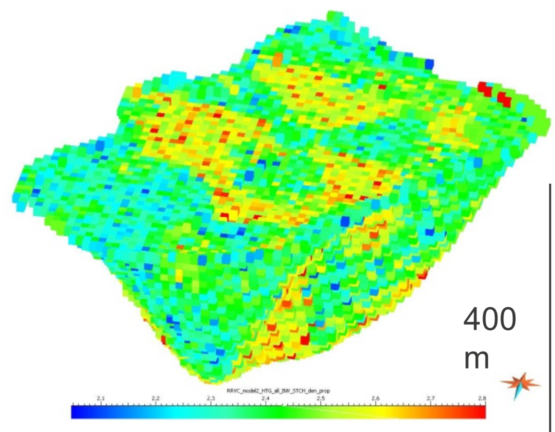


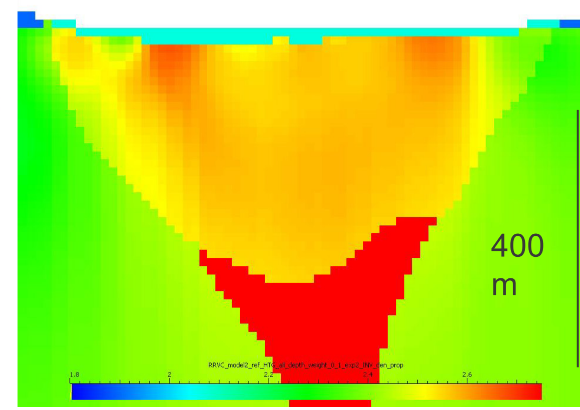


Multiple coalesced broad, shallow
diatreme structures
Indicates vent migration

Complex internal structures with multiple intrusions and/or remnant feeder vents

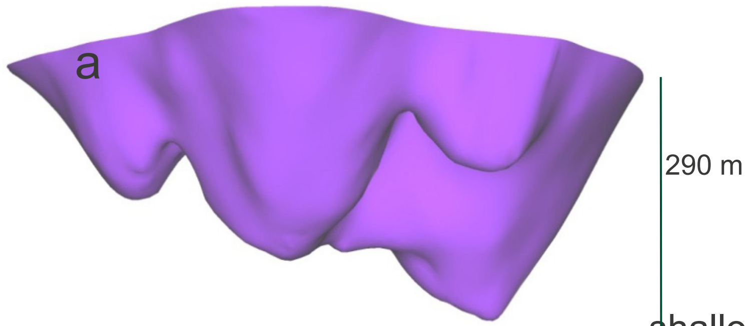


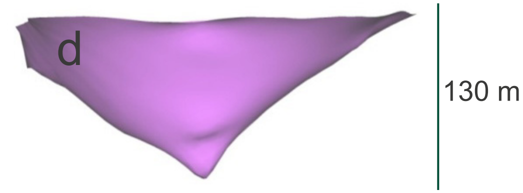




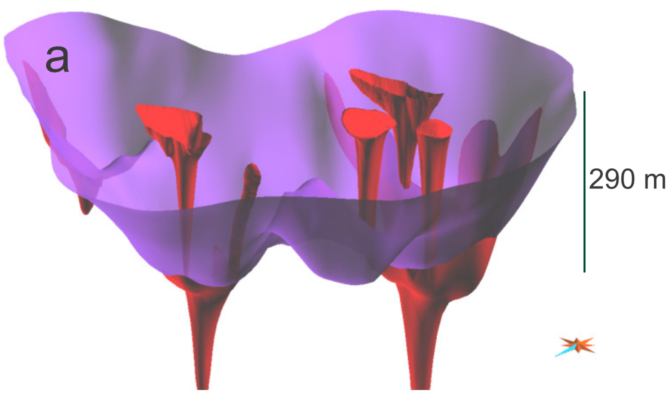
Red Rock – 3D models

Multiple coalesced diatreme structures
- Indicates vent migration

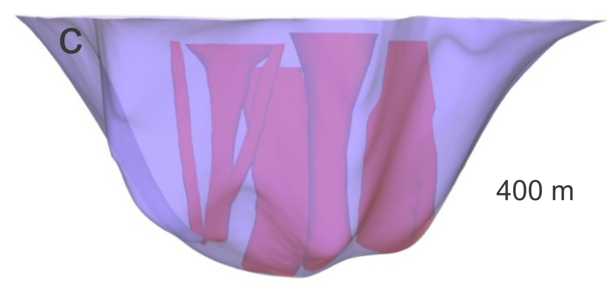


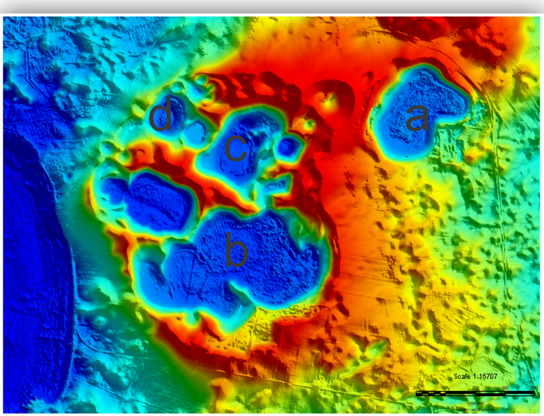


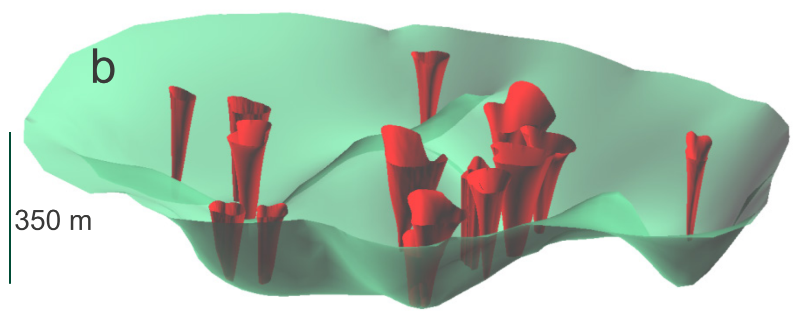
Broad, shallow diatreme.
shallow eruption - no downwards propagation of magma-water interaction depth



Complex internal structures with multiple intrusions and/or remnant feeder vents

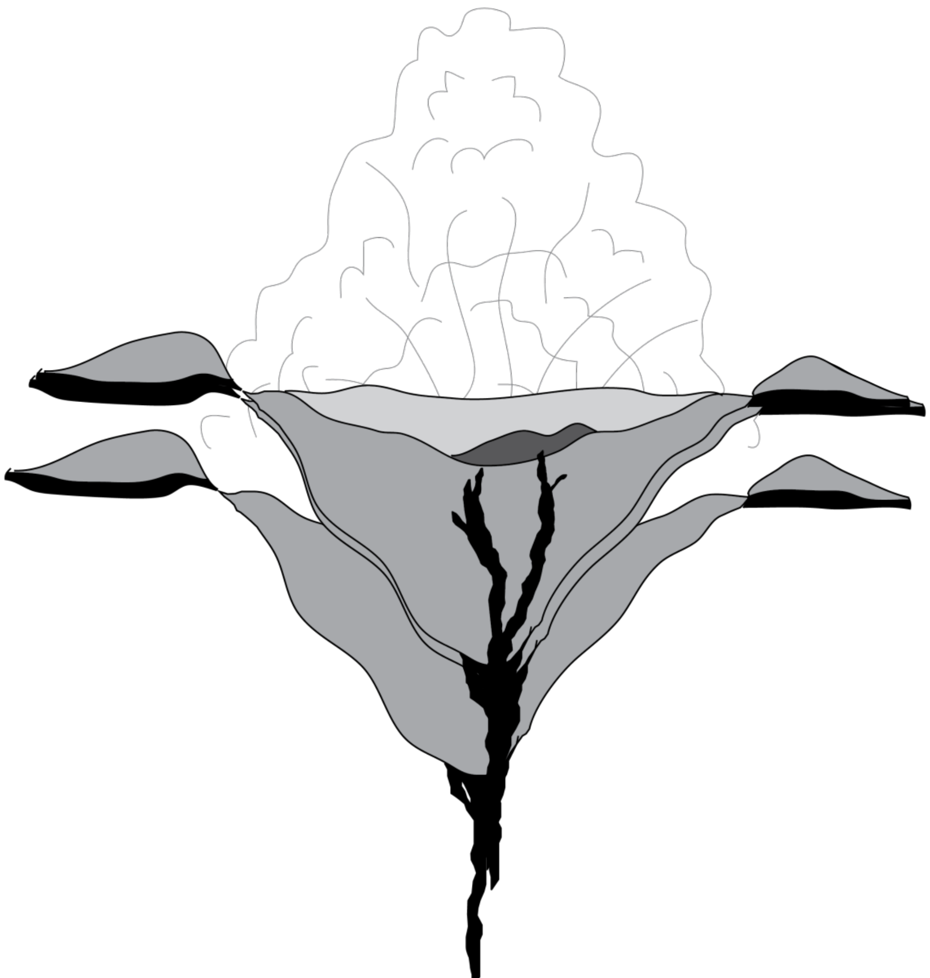






Piganis (2011)

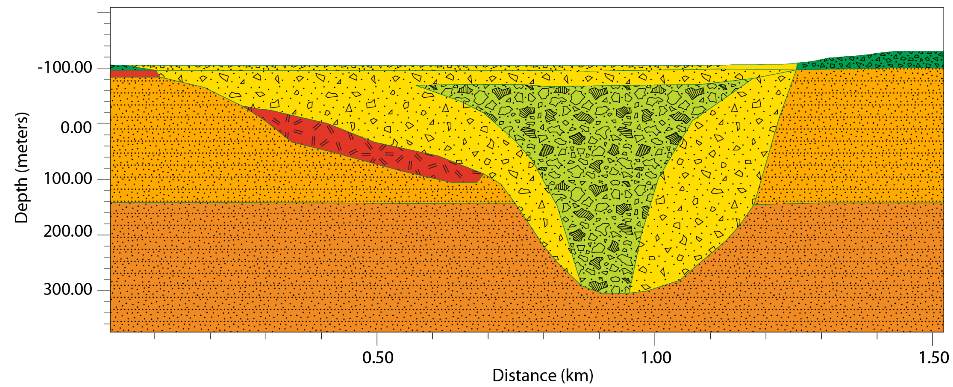
Volcanic Evolution

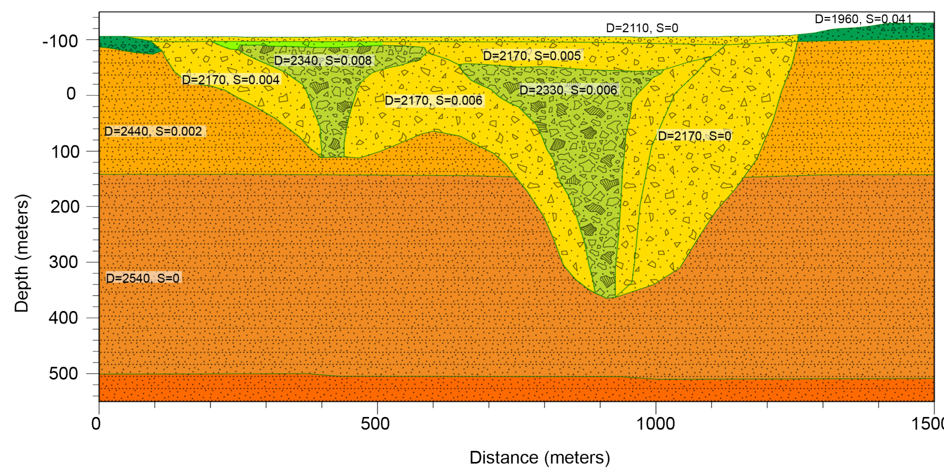


- Initial eruption forming maar crater
- Dykes rise the surface, explosive magmatic eruptive style
  - Frequent switches between magmatic/phreatomagmatic
- Lake formation, sedimentation

Model Ambiguity

- Potential field models are non-unique, and many models can be constructed that may reproduce the observed anomalies.
- Ambiguity arises because there is no unique solution to the data
- Make assumptions in the model
  - Because we are unable to directly sample and measure the properties of the diatreme
- To reduce model ambiguity
  - Models should be consistent with all geological information
  - Link geophysical observations with geologic observations and volcanic processes
- **No particular model is 'correct'. Produce multiple models that highlight different features**

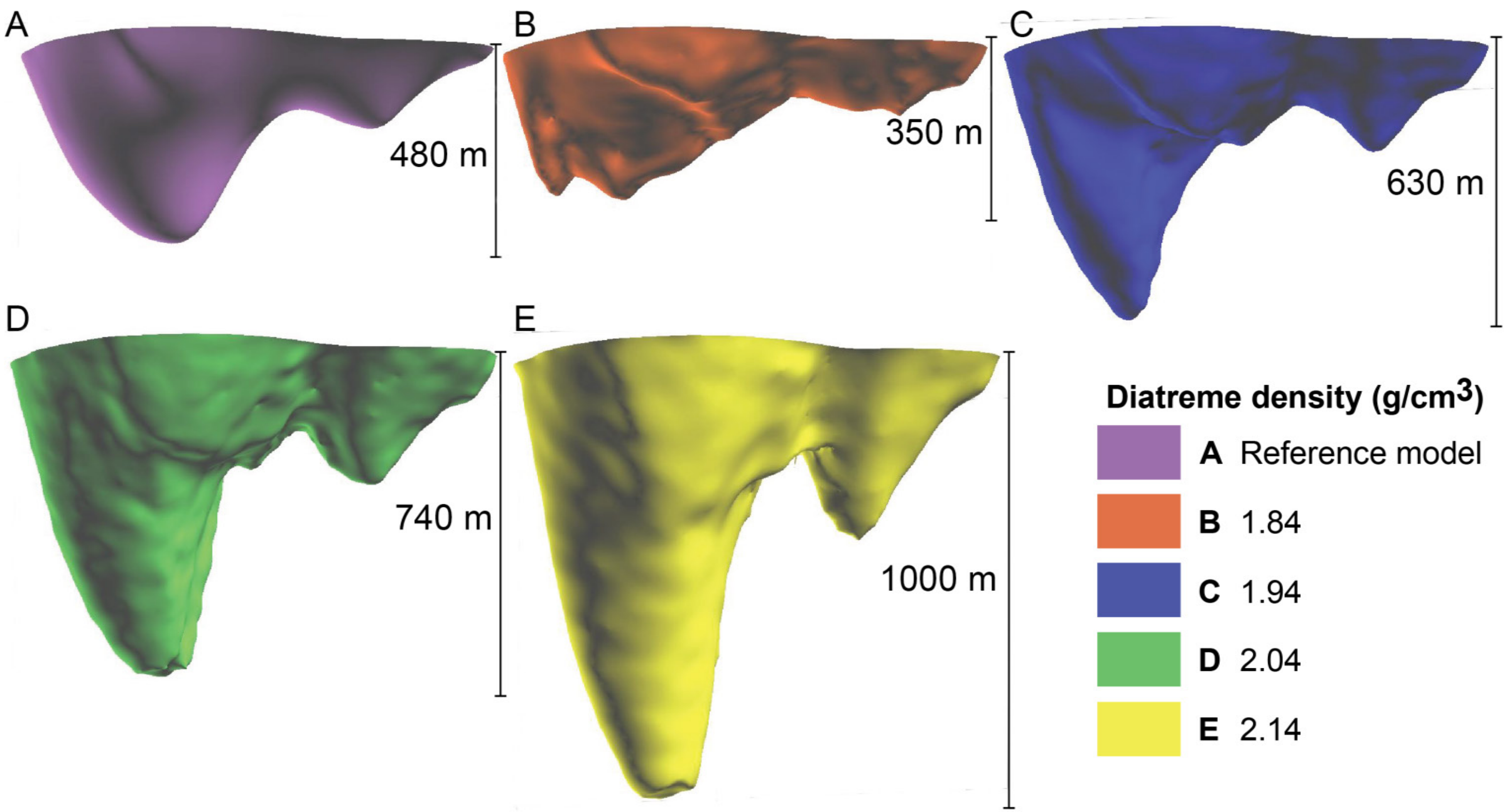




3D geometric sensitivity analysis

- Model properties remain fixed, geometry is allowed to vary
- Maar-diatreme can't be sampled directly to determine density
  - Density of pyroclastic deposits is used as an analogue
- We can calculate what the optimum geometry would be if we assign a different density to the diatreme

3D geometric sensitivity analysis

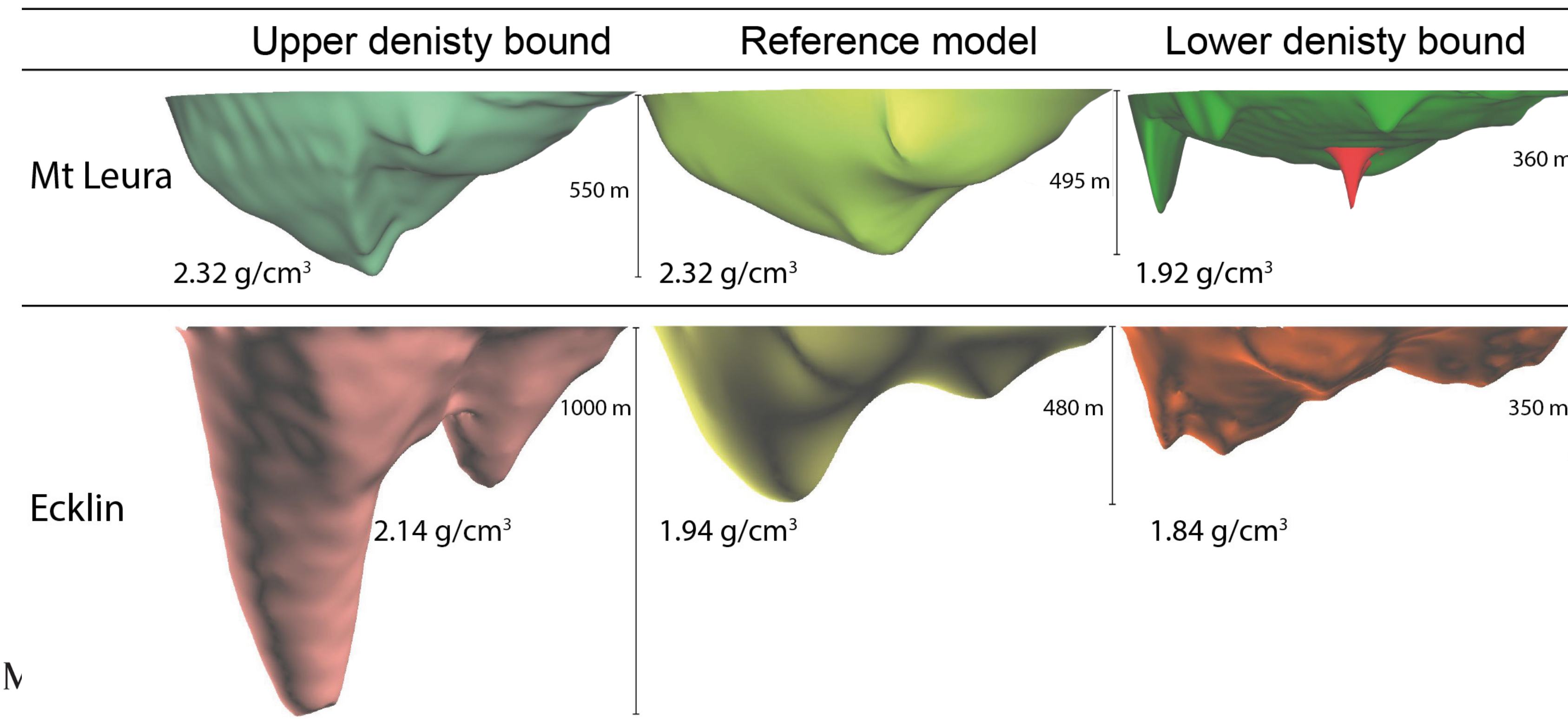


3D geometric sensitivity analysis

- Ambiguity arises as there is no unique solution to the data, and because of the assumptions we made during modelling

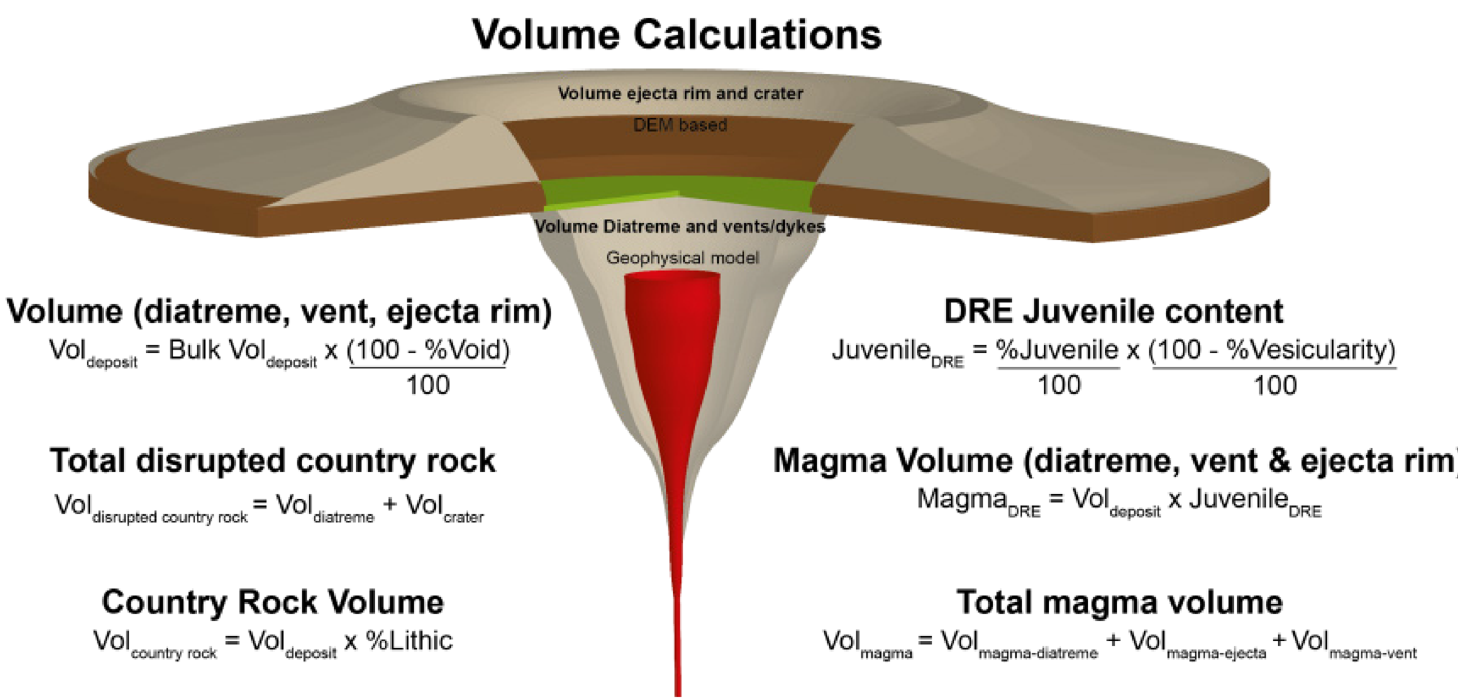
- Sensitivity analysis lets us determine how a models geometry might vary within the bounds of the constraints.

- **No particular model is 'correct'. Produce multiple models that are consistent with geologic constraints.**



Magma volume estimates

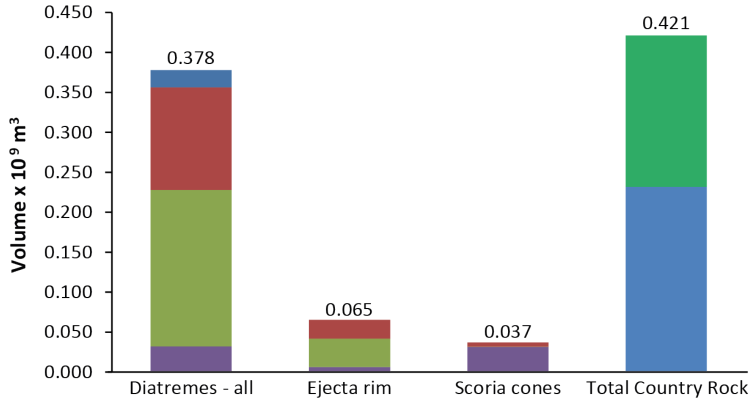
- 3D geophysical models allow an estimate of the total volume of magma involved in each eruption.
- Import constraint in estimating size (VEI) of the eruption and eruption durations



Constraints

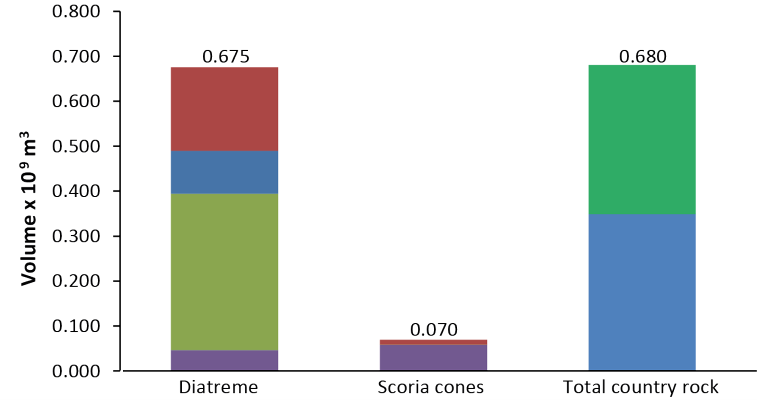
Volcanic centre	Lithic content %	Juvenile content %	Vesicularity %	Porosity/Void space %
Phreatomagmatic deposits				
Red Rock	55	45	20	1
Ecklin (diatreme)	75	25	15	1
Ecklin (vents)	40	60	15	1
Mount Leura	60	40	20	1
Magmatic deposits				
Red Rock	1	99	64	60
Mount Leura – Scoria	1	99	60	60
Mount Leura – Lava	0 %	100	10	0

A. Red Rock Volcanic Complex



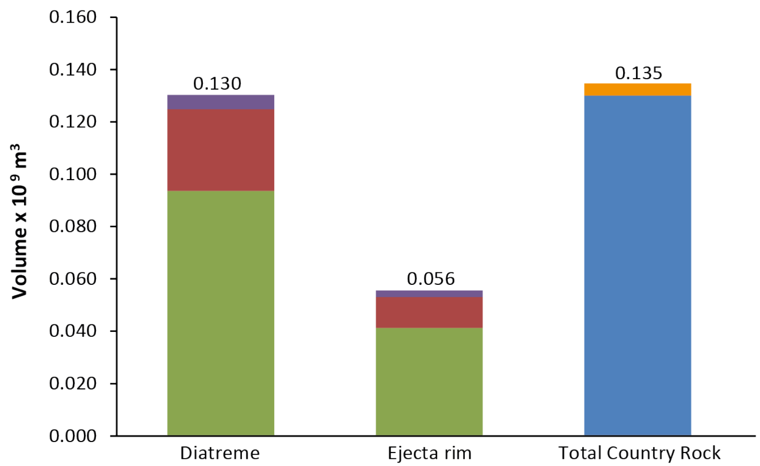
	Diatremes - all	Ejecta rim	Scoria cones	Total Country Rock
Magma - dykes and lavas	0.022	0.000	0.000	
Magma (DRE)	0.128	0.023	0.005	
Country rock	0.196	0.036	0.000	
Inter-particle void/vesicles	0.032	0.006	0.031	
Unaccounted country rock				0.189
Accounted country rock				0.232

C. Mount Leura Volcanic Complex



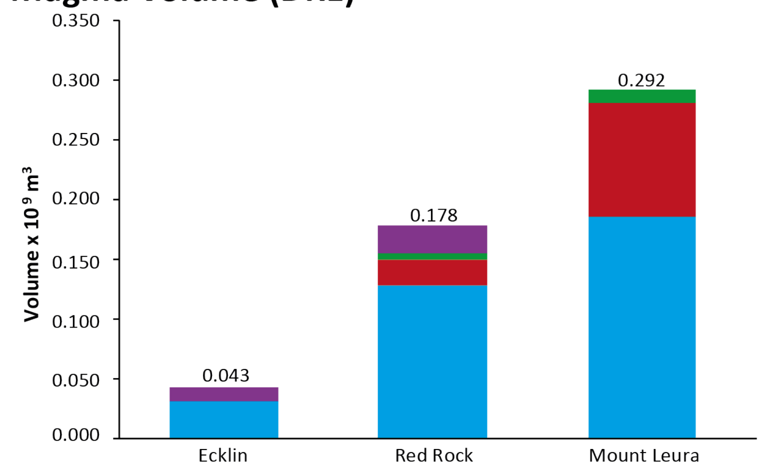
	Diatreme	Scoria cones	Total country rock
Magma (DRE)	0.186	0.011	
Magma - dykes and lavas	0.095	0.000	
Country rock	0.348	0.001	
Inter-particle void/vesicles	0.046	0.058	
Unaccounted country rock			0.332
Accounted country rock			0.349

B. Ecklin



	Diatreme	Ejecta rim	Total Country Rock
Magma (DRE)	0.031	0.012	
Country rock	0.093	0.041	
Inter-particle void/vesicles	0.006	0.003	
Accounted country rock			0.130
Over-accounted country rock			0.005

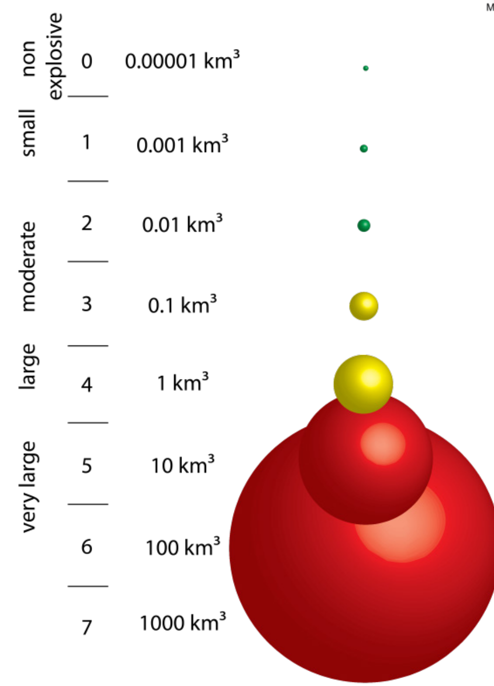
D. Total Magma Volume (DRE)



	Ecklin	Red Rock	Mount Leura
Ejecta rim	0.012	0.023	
Cones		0.005	0.011
Dykes and Lavas		0.022	0.095
Diatreme	0.031	0.128	0.186

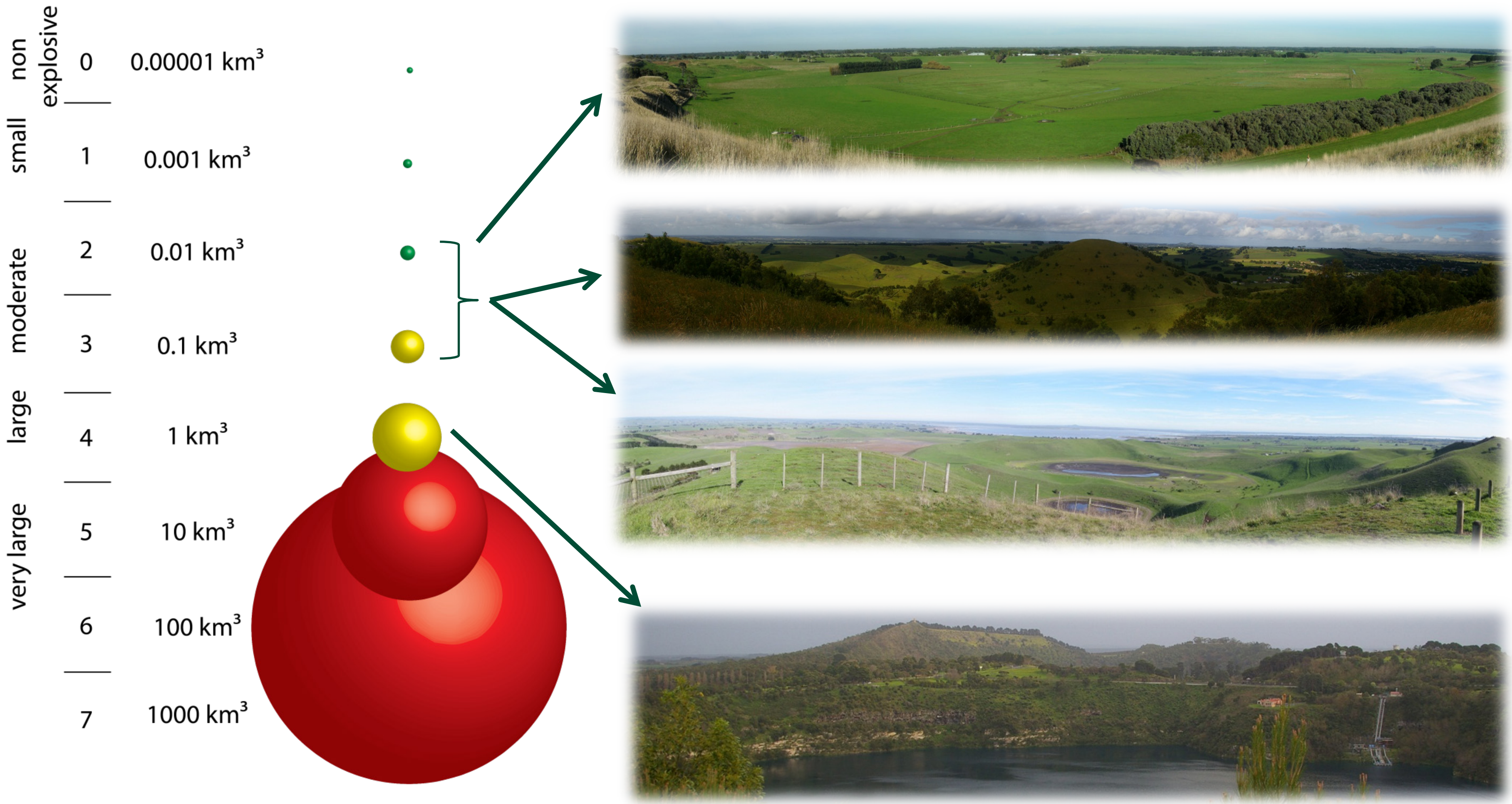
VEI Index

- VEI is difficult to determine in these cases because of multiple vents
- Based on proximal tephra volumes, these volcanoes are classified as VEI 2.
- But Red Rock and Mt Leura could have reach VEI 3 if the eruption from the multiple vents were continuous and eruption column heights > 3 km were sustained



Volcano	Total erupted tephra x 10^9 m^3	DRE Erupted Tephra x 10^9 m^3	Total DRE Magma volume x 10^9 m^3	Erupted DRE magma volume x 10^9 m^3	VEI Index
Ecklin	0.056	0.05	0.043	0.012	2
Red Rock	0.10	0.06	0.17	0.029	2*
Mt Leura	0.07 (cones only)	0.01	0.29	0.01	2*

Maar eruptions in the NVP



Eruptions of the maars at Ecklin, Red Rock and Mt Leura are comparable to Ukinrek (1977) eruption.

- Produced an eruption column 6 km high. Dispersed ash at least 160 km from the vent
- Potential for future eruptions to impact modern infrastructure

Summary

- Geophysical modelling has identified complex maar-diatreme structures:
  - Shallow maar-diatremes with multiple vents – related to weakly lithified host rock
    - Water saturated sediments prevent downward propagation of explosions
    - Collapse of host rock/pyroclastic debris, clogging the vent and resulting in vent migration
  - Evidence of longer wavelength, low amplitude gravity and magnetic anomalies within the maar (Ecklin)
    - Represents debris jets being entrained into to diatreme, forming sub-vertical zones with higher volumes of volcanic debris
  - Presence of dykes and lava flows creates high amplitude, short-wavelength anomalies (Mt Leura)
    - Caused by groundwater drying up, allowing magma to rise to surface and erupt in a magmatic style

- **Hazard implications**
  - Deep explosions are confined by the crater, and overlying diatreme fill and are unlikely to erupt, or eject large volume of debris from crater
  - **Shallow explosions are more likely to erupt, and will disperse volcanic ash over a wider area (i.e., Melbourne!)**

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